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(54) A SYSTEM OF OVERLOAD PROTECTION BY USING SUPERCONDUCTING CONDUCTORS

(71) We, LICENTIA PATENT-VERWALTUNGS G.m.b.H., of 1 Theodor-Stern-kai, 6 Frankfurt 70, Germany, a German Body Corporate, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The invention relates to a system for the overload protection of normally conducting or superconducting apparatus equipment, machines or circuits in direct-current or alternating-current installations using superconducting conductors or conductor structures which are restored entirely or over a considerable proportion of their extent to the normal conducting state by a magnetic field caused by factors such as overload state or voltage drop appearing in the event of overloading.

The increasing interconnection of modern current supply mains and increase in the capacity of generating plant render necessary ever more rapid disconnection of faulty parts of the mains in the event of a breakdown.

Accordingly, high-capacity circuit-breakers have been developed with corresponding tripping devices (relays etc) with which it is possible to achieve short-circuit durations of a few half-waves (30—50 milliseconds duration). Such circuit breakers are, however, extremely expensive because they have to be dimensioned for switching off the entire short-circuit power.

According to the invention there is provided a system for the overload protection of normally conducting or superconducting apparatus, equipment, machines or circuits in direct-current or alternating current installations with one or more superconducting conductor elements, which is or are connected in series with the load circuit, which element or elements is or are influenced, in the event of a fault, by an external magnetic field of such a magnitude that the super-conducting conductor element or elements is or are brought into the normal conducting state over an extent such that a resistance is built up sufficient to prevent heating up to melting point of the point of the superconducting conductor element or elements which is quenched first by the field in a time less than that required for said point to reach melting point, wherein the magnetic field serving to quench the conductor element or elements is caused by a magnetic coil which surrounds the conductor element or elements.

The invention will now be described in greater detail by way of example, with reference to the accompanying drawings, in which:—

Figures 1 to 3 show known forms of overload protection systems;

Figure 4 shows one form of an overload protection system in accordance with the invention;

Figures 5 and 6 show two forms of energising coil such as are used in the embodiment of Figure 4;

Figure 7 shows a second form of an overload protection system in accordance with the invention;

Figures 8 and 9 shows graphically the behaviour of the actuating current and rate of rise of the actuating current against time for protection systems in accordance with the invention.

Figure 10 shows graphically the behaviour of the quenching field in a protection system in accordance with the invention;

Figures 11 to 14 show further embodiments of the invention.

For overload protection it would be possible to consider connecting a resistor R or other impedances which are bridged by a circuit-breaker S_1 (see Figure 1) in the normal operating state, in series with the devices to be protected, for example a cable, K in the event of a fault and so to limit the short-circuit current. The main circuit-breaker S_2 would then have to be dimensioned not for the short-circuit current but for a correspondingly lower current. Nevertheless, the disconnection

problem would merely be shifted from the circuit-breaker S_2 to the circuit-breaker S_1 which would have to be dimensioned for a high circuit-breaking capacity, nor would any improvement be achieved with regard to the circuit-opening times.

In recent times, therefore, short-circuit limiting devices have been proposed with the aid of supersaturated reactor coils and capacitors (see Elektrotechnische Zeitschrift Edition A 1966, pages 681—685) which entirely prevent the development of the full short-circuit current in the event of a fault. Such devices are likewise expensive, however, and involve heavy costs.

It has already been proposed (see Mac Fee: Electrical Engineering Feb. 1962 pages 127 and 128 " Applications of Superconductivity ") that superconducting wires (which have as high a resistance as possible in the normal conducting state) mounted in a Dewar flask G should be connected in series with the devices to be protected (see Figure 2) and should be so dimensioned that under normal current loading they remain superconducting (that is to say have no resistance with direct current and only an extremely low resistance with 50 cps alternating current), change over to the state in which they conduct normally in the event of excess current appearing as a result of heavy current loading or as a result of their characteristic magnetic field, and limit the short-circuit current by means of the ohmic resistance which they thus acquire. In contrast to cryotrons which have proved satisfactory in the communication art (with low voltages), however, such devices do not appear to be suitable for heavy-current engineering, particularly high-tension engineering.

Because of the impossibility of manufacturing wires having completely homogeneous characteristics along their whole extent, the changeover from superconducting to normal conducting always takes place initially at a locally limited point *St* (see Figure 3) at which the wires D in the Dewar flask G first conduct normally, suddenly become heated under the influence of the severe short-circuit current, and burn through so that the whole mains voltage becomes effective there and produces an arc L with the full short-circuit power which is just as difficult to interrupt by means of the main circuit-breaker S as the short-circuit current appearing without this protective device (see Figure 3).

The invention, therefore, proposes basically to prevent the development of the full short-circuit current by means of one or more superconducting elements which are connected in series with the devices to be protected and which are brought into the normal conducting state in the event of a fault through influencing the element or elements by means of magnetic fields along their *whole* extent or at least over a considerable proportion of their extent, and reduce the short-circuit current by the ohmic resistance which they then assume.

Such systems according to the invention appear suitable not only for the overload protection of conventional apparatus, machines, equipment and circuits, but, in particular, also for devices in which superconducting conductors or low-temperature high-purity metal conductors are used (superconducting transformers, machines, cables etc.), because then low-temperature cooling devices are already available on the spot for production of liquid helium or hydrogen.

Figure 4 shows a short-circuit protection system in accordance with the invention for a single-phase cable K which may be conventional (or may itself consist of superconductors). In the interior of an energising coil, *Sp*, through which the conductor current flows, there is a low-temperature cooled superconducting wire D along the whole length of the coil. The number of turns in the energising coil is such that when a maximum permissible current density of the conduction current or a maximum permissible rate of rise of the current is exceeded, " quenching " occurs, that is to say destruction of the superconductivity of the wire D (hereinafter briefly termed " quenching "). In order to achieve adequate ohmic resistance in the wire D in the quenched (normally conducting) state or in order to influence it by means of magnetic lines of flux entering it radially within the coil *Sp*, it may be advisable, according to the invention, to make the wire D multifilar inside the coil *Sp* (see Figure 5) or to construct it in the form of a bifilar wound coil (see Figure 6). By selection of the material, of the length and of the cross-section of the wire D, and hence of a resistance in the quenched state, it is then possible to limit the short-circuit current of the device to be protected (for example a cable) in the required manner and to design the power circuit-breaker S for a lower power than the whole short-circuit power.

In dimensioning the cross-section of the wire D, care must be taken to ensure that in normal operation it is not already quenched by the magnetic field created at its surface by the current flowing in it itself, and converted in to the normal conducting state (with resistance). This can be achieved economically in known manner by dividing the wire D into a relatively large number of conducting strands which are connected in parallel and which lead to the load because the magnetic field strength appearing at the surfaces of the conductors are in the relationship

$$H=\frac{S.R}{2}$$

to the radii R of the conductors and their current density S, and individual conductor strands have scarcely any mutual magnetic influence on one another.

Superconducting wires or wire structures which are exposed to the magnetic field of individual quenching coils or the magnetic field of a common quenching coil may be used both in the outgoing and return line (in all three phases with three-phase current), while the corresponding conductor current or, if current transformers are used, currents which are proportional thereto, may flow through the quenching coils.

It is also possible (and in many cases even an advantage) to derive the current for building up the quenching field in the energising coil Sp from an external energy store, for example a storage battery or a bank of capacitors, which is brought into action when a specific actuating current (I_a see Figure 8) or a specific value of the rate of rise of the current ($(dI/dt)_a$ see Figure 9) is reached. (In these figures the suffix N relates to normal crurent and the suffix K relates to short circuit current) The actuating current value I_a or the value of the rate of rise of the current (dI/dt_a (see Figures 8 and 9) should be selected in such a manner that the power circuit-breaker causes disconnection of the circuit to be protected before the permissible instantaneous current value I_z is reached, (that is disconnection should take place within the time t_v available for the safety device to act, see Figure 8 and Figure 9). As can be seen from Figures 8 and 9, more time t_v is available for the time disconnection by means of the power circuit-breaker in the event of its being controlled through the value of the rate of rise of the current $(dI/dt)_a$ than in the event of its being controlled through the current actuating value I_a.

Figure 7 shows an embodiment of the invention. The low-temperature superconducting protective wire D or a corresponding wire structure, accommodated in a Dewar flask G, is connected in series with the device to be protected (for example a cable) and is completely inside a Helmholtz coil *Sp* producing a homogeneous field. In order to achieve a magnetic field rising as rapidly as possible in the Helmholtz coil, it is advisable to construct the Helmholtz coil with as low an inductance as possible, that is to say with only a few turns (in the extreme case two) and to use as a conductor for it a copper tube or a superconductor having a high quenching field strength (low time constant because of the low inductance and the skin effect losses which are then limited). The Helmholtz coil may be accommodated either inside or outside the Dewar flask G (which in the latter case must consist of a material which is non-conducting or is a poor conductor). Connected electrically in series with the device to be protected (for example a cable) is a current transformer with the windings W_1, W_2, the secondary winding of which leads to a control spark gap Z_1, Z_2. When a specific adjustable value of the rate of rise of the current ($(dI/dt)_a$ Figure 9) is exceeded, that is to say a voltage proportional to this value in the secondary winding W_2 of the transformer, flashover occurs between the electrodes of the control spark gap Z_1, Z_2 and consequently also the firing of a spark gap between the switching electrodes E_1, E_2 as a result of which the bank of capacitors C—previously charged by the battery B—is discharged across the Helmholtz coil in which it produces the abrupt magnetic field necessary for the quenching of the superconducting protective wire D or a corresponding wire structure D (see Figure 10, magnetic field H, time *t*). Through appropriate dimensioning of the resistance of the wire or wire structure D in the quenched state, it is possible to limit the short-circuit current. The power circuit-breaker S which may receive its tripping impulse, for example likewise from the secondary side of the current transformer, need then only control a current strength which is limited to the normal operating current for example, even in the event of a fault.

Instead of actuating the bank of capacitors by means of spark gaps, electronic actuation may, of course, also be used, for example with thyristors or the like.

Figure 13 shows a corresponding device in a block circuit diagram. The voltage appearing at a normal conducting or superconducting reactor coil D*r*, connected in series with the circuit to be protected, is compared, in an electrical difference network DG, with an adjustable desired voltage value. If it exceeds the desired value in the event of a shirt-circuit, then a pulse is produced in the difference network and, after appropriate amplification (amplifier V) serves to actuate the switching thyristor T through which the bank of capacitors C, previously charged by the battery B through the auxiliary switch HS, is discharged across the Helmholtz coil S*p* and causes the quenching of the protective wire D, as described previously.

It appears to be advisable to effect the switching-on the battery B (see Figures 7 and 13) from which the bank of capacitors C is charged, through an auxiliary circuit-breaker HS coupled to the main circuit-breaker S (see Figures 7 and 13) in such a manner that when the main circuit-breaker S is opened, the auxiliary circuit-breaker HS is closed and so the bank of capacitors is charged. When the main circuit-breaker is again connected to the mains (for example in the event of automatic closure under short-circuit conditions) the auxiliary circuit-breaker HS is opened (see Figure 7) in order to prevent discharging of the battery B across the

coil Sp during the whole short-circuit period. Experiments have shown that the protective wire D quenched by the very brief shock magnetic field of the capacitor discharge in the Helmholtz coil in the event of a short-circuit remains in the quenched (normal conducting) state under the influence of the damped short-circuit current flowing through it for the duration of the short-circuit. It therefore does not appear necessary for current to be admitted to the Helmholtz coil from the battery up to the moment when the main circuit-breaker is opened. It would merely lead to superfluous vaporisation of helium if the Helmholtz coil is a cooling vessel.

All the examples described so far still have the disadvantage (see Figure 7 or Figure 13 for example) that on the appearance of a short-circuit, short-circuit current (although damped) flows in the quenched (that is to say normally conducting) wire or wire structure D until the device to be protected (for example a cable) is disconnected by the main circuit-breaker S and causes considerable heat action in the normal conducting wire or wire structure D and hence extensive vaporisation of the coolant (for example liquid helium) which means a corresponding undesirable power consumption for the refrigerators.

This disadvantage can be overcome in that a normally cooled resistance, for example an iron conductor Fe, the ohmic value of which corresponds to only a fraction of the ohmic value of the wire or wire structure D in the quenched state, is connected in parallel with the wire or wire structure D which is in the Dewar flask (see Figure 11). Whereas, in normal operation, the conductor current flows through the superconducting wire (or the wire structure) D, the direct-current resistance of which is equal to zero, and the alternating-current resistance of which corresponds to only an infinitesimal fraction of the resistance of the normally cooled iron conductor Fe connected in parallel, in the event of a short-circuit (after the quenching of the wire or wire structure) the main portion of the "short-circuit current" is conveyed through the normally cooled resistor Fe. The generation of heat in the quenched wire or wire structure D and hence the consumption of coolant (for example liquid helium) can be considerably restricted as a result.

Through appropriate dimensioning of the normally cooled resistor Fe (see Figure 11) it is possible, for example, to adapt the resulting resistance afforded by the parallel connection of the wire D and the normally cooled resistor Fe after the quenching of the protective wire D in such a manner that its ohmic value corresponds to the load impedance. The current to be interrupted by the power circuit-breaker in the event of a short-circuit then corresponds to the normal operating current and the power circuit-breaker does not have to be dimensioned according to the short-circuit current, as otherwise usual, but only in accordance with the normal operating current. It can therefore be less expensive and smaller in construction.

In order to obtain a sufficiently high resistance *after* the quenching (that is to say sufficiently great damping of the short-circuit current) from protective wires or protective wire structures consisting of superconducting materials in the quenched state, despite the fact that the specific resistance is none too high, without being forced to use lengthy and therefore expensive and voluminous arrangements, it may be an advantage to provide the superconducting material of the protective wires only in the form of a thin layer on carrier wires having a high specific resistance. Figure 14 shows the corresponding example of an embodiment of the idea of the invention. A manganin wire M having a high specific resistance even at the lowest temperatures carries on its surface a covering of niobium Nb only a few μ thick and is disposed in the interior of a Helmholtz coil as in the examples previously discussed (for example Figure 11), and a resistor Fe which is cooled normally, for example with water, is connected in parallel therewith.

Apart from the resistances, which disappear completely with direct current and are extremely low with alternating current at low frequency (for example 50 cps), the so-called introduction losses of the current conductors in the Dewar flask play a considerable part in extremely low-temperature heavy-current engineering devices and allowance must be made for about 1 watt loss for each ampere of current which is introduced into the Dewar flask. This is due to the Wiedemann-Franz law according to which good current conductors are always good heat conductors also and heat penetrates into the Dewar flask by heat conduction along the current conductor at the points of introduction of the current conductors into the Dewar flask (which current conductors have to be robust in dimensions in view of the excessive electrical losses which would otherwise occur therein, in conductor sections not yet superconducting.

In order to obtain economical solutions to the overload protection, it may be advisable, in the case of the example of Figure 7, to use electrolytic capacitors with which large energies can be stored. Such capacitors must, however, be used only in *one* current direction and must be protected from high-voltage surges. Since at the initiation of the short-circuit with alternating-current loading, the current rise may occur either in the positive or in the negative sense, it is proposed that a full-wave rectifier G1 should be connected into the secondary circuit of the current transformer Str (see Figure 13), which rectifier

feeds a small transformer *Tr* through the secondary voltage of which, firing of the switching spark gap *Sch* is effected. It is then possible, as Figure 13 shows, to avoid both incorrect admission to the electrolytic capacitors C and—through parallel connection of the rectifier G1—also high-voltage shock-loading of the electrolytic capacitors (see Figure 13).

In a modification of the arrangements above described, the current for the quenching coil is provided by the secondary circuit of a current transformer.

WHAT WE CLAIM IS:—

1. A system for the overload protection of normally conducting or superconducting apparatus, equipment, machines or circuits in direct-current or alternating current installations with one or more superconducting conductor elements, which is or are connected in series with the load circuit, which element or elements is or are influenced, in the event of a fault by an external magnetic field of such a magnitude that the superconducting conductor element or elements is or are brought into the normal conducting state over an extent such that a resistance is built up sufficient to prevent heating up to melting point of the point of the superconducting conductor element or elements which is quenched first by the field in a time less than that required for said point to reach melting point, wherein the magnetic field serving to quench the conductor element or elements is caused by a magnetic coil which surrounds the conductor element or elements.

2. A system of overload protection as claimed in Claim 1, wherein the load current or a current derived from an external source of energy switched in response to a fault in the load circuit flows through the magnetic coil.

3. A system of overload protection as claimed in Claim 1 or 2, wherein the magnetic field which is brought into action by the fault is assisted by the magnetic field produced by the current in the conductor element or elements themselves.

4. A system of overload protection as claimed in Claim 2, wherein an external source of energy is used which source is caused to act in the event of a fault when a specific instantaneous value of the short-circuit current is exceeded.

5. A system of overload protection as claimed in Claim 2, wherein an external energy source is used which source is caused to act in dependence on the rate of rise of the current in respect of time of the short-circuit current.

6. A system of overload protection as claimed in Claim 2 or 5, wherein the external source of energy is caused to act by the firing of a spark gap when a specific rate of rise of the current is exceeded, using a voltage proportional to this rate of rise of the current.

7. A system of overload protection as claimed in Claim 2 or 5, wherein the external source of energy is actuated by electronic means, when a specific rate of rise of the current is exceeded, by means of a voltage proportional to this rate of rise of the current.

8. A system of overload protection as claimed in Claim 7, wherein the electronic means include comparison circuits and thyristors.

9. A system of overload protection as claimed in Claim 1, wherein the current serving to provide the magnetic field for quenching the superconducting element or elements derived from the secondary circuit of a current transformer.

10. A system of overload protection as claimed in any one of Claims 1 to 9, wherein a or the coil serving to produce the quenching field is constructed in the form of a Helmholz coil.

11. A system of overload protection as claimed in Claim 10, wherein the Helmholtz coil has only a few turns.

12. A system of overload protection as claimed in Claim 10, wherein the Helmholtz coil has two turns.

13. A system of overload protection as claimed in any one of claims 10 to 12, wherein the wires of the Helmholz coil consist of a tubular conductor.

14. A system of overload protection as claimed in any one of Claims 10 to 13, wherein the wires of the Helmholtz coil consist of a superconducting conductor which tolerates higher critical field loading than the conductor element or elements, to be quenched.

15. A system of overload protection as claimed in any one of Claims 1 to 14, wherein the magnetic coil serving to produce the quenching field consists of high-purity metal and is cooled to an extremely low temperature.

16. A system of overload protection as claimed in any one of Claims 4 to 8 and Claims 10 to 15 when appendent directly or indirectly to claim 2, wherein the external source of energy consists of capacitors.

17. A system of overload protection as claimed in Claim 16, wherein the external source of energy consists of electrolytic capacitors.

18. A system of overload protection as claimed in any one of Claims 4 to 8 and Claims 10 to 15, when appendent directly or indirectly to claim 2, wherein the external source of energy is formed by accumulators.

19. A system of overload protection as claimed in any one of Claims 1 to 18, wherein the superconducting conductor elements are bifilar or multifilar in arrangement inside the magnetic coil.

20. An overload protection system substantially as described with reference to any of Figure 4 to 7 and 11 to 14 of the accompanying drawings.

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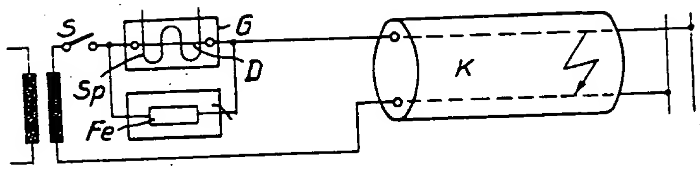


Fig.11

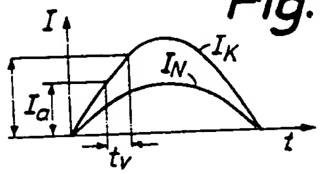


Fig.8

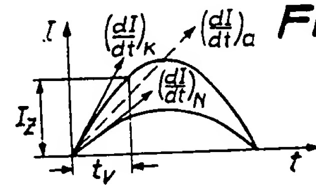


Fig.9

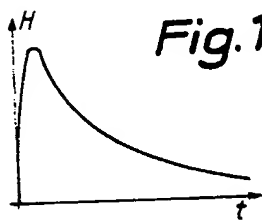
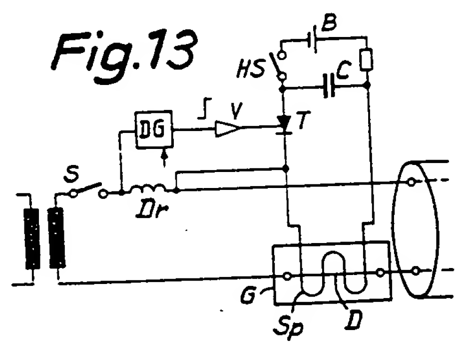


Fig.10

Fig.13


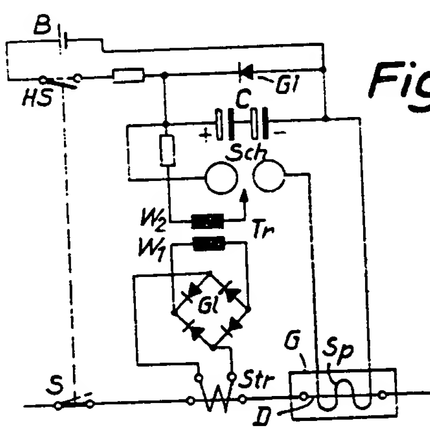
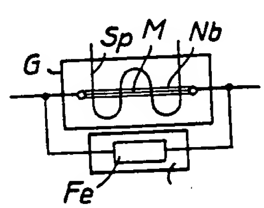


Fig.12

Fig.14


1236082 COMPLETE SPECIFICATION

2 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

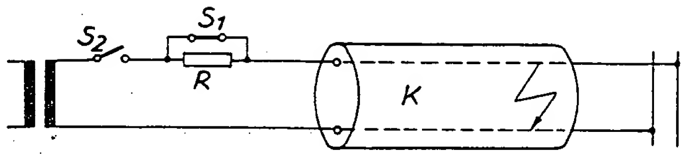


Fig.1

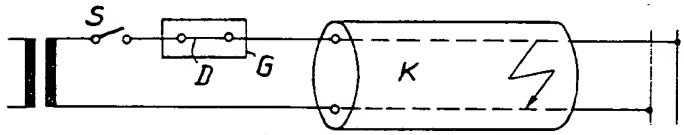


Fig.2

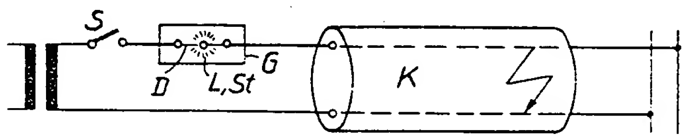


Fig.3

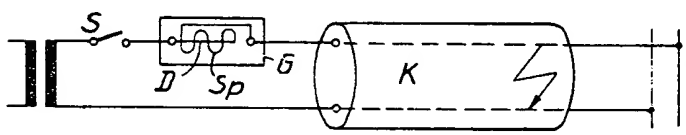


Fig.4

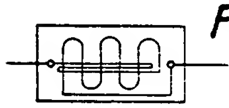


Fig.5

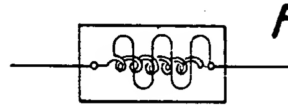


Fig.6

Fig. 7